SPATIAL ANALYSIS OF TIDAL RIVERS IN THE CONTINENTAL UNITED STATES

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Abstract

Coastal rivers can experience tidally-induced stage fluctuations due to their close proximity to the ocean. Information about the extent of tidal influence is essential because an increasing number of people rely on tidal rivers for both drinking water and recreation, and sea-level rise will likely alter river levels and water quality in the coming decades. While previous studies have examined the ecology of tidal rivers, this study analyzes locations of tidal influence in the continental United States using USGS stream hydrographs and the National Hydrography Dataset. Of the 4,834 coastal gauges surveyed, approximately 8% (383) are tidally influenced. Tides extend up to 47km inland. Tidal gauges have a mean elevation of -0.29m below sea level. Dams and other manmade structures as well as natural riffles and waterfalls obstruct the flow of tides. Due to the scarcity of data for tidal rivers, more expansive stream-gauging networks are needed in coastal regions to better document tidal influence on rivers.

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INTRODUCTION

Tides in undammed rivers can extend hundreds of kilometers inland (Odum et al, 1984). With the majority of the population of the United States living on or near the coast (NASA, 2000), it is important to understand the influence of humans on tidal rivers and water quality. The tidal system extends upstream to the head of tide (limit of tidal influence) and downstream to the open ocean. Along this continuum, salinity increases through oligohaline, mesohaline, and polyhaline zones (Odum, 1988). Variation in salinity and morphology throughout the tidal system provides habitats for grasses, shrubs, fish, snakes and mussels (Odum et al, 1984). Tidal freshwater zones lie at the upstream end of the continuum where water is predominately fresh and flow is channelized.

Much of what is known about tidally influenced rivers is related to the ecology of their marshes and wetlands. Previous studies of tidal rivers focus on the variation in plant and animal life (Odum et al., 1984), while others focus on the effects of changing salinity on tidal wetlands (Noe et al., 2012). Amazingly, little is known about the hydrology, water quality, and extent of tidally influenced rivers, though large populations depend on them as sources for drinking water and recreation. The population in coastal counties was 87 million in 2008 (28% of the total US population) and has nearly doubled since 1960 (Wilson and Fischetti, 2010). Human activities near tidal rivers can influence local surface water resources and downstream water quality. Fertilizer application and leaky septic tanks supply excess nitrogen (N) to the system, fueling algal blooms and deteriorating vital fisheries (Howarth, 2008). Tidally influenced rivers are also subject to disturbance from rising sea level. The projected eustatic sea level rise from 2081-2100 is between 0.26 and 0.82m (Edenhofer et al., 2014), which may radically affect low-gradient coastal reaches in the next century. It is important that we understand the extent of tidally influenced rivers so that we can monitor their response to anthropogenic pressures and rising sea levels.

The extent and number of tidal rivers is largely unknown, even in the United States where high-resolution spatial datasets exist. In this study, I analyze USGS stream flow data to identify tidally influenced rivers of the continental United States. I assess where they occur and their possible inland extent, while discussing the data needs and research opportunities necessary to better monitor their status.

METHODS

River stage records were examined from the United States Geological Survey's (USGS) water database for all gauging stations within East, West and Gulf coast states (U.S. Department of the Interior, NWIS). A total of 4,834 gauges were analyzed (Figure 1). For each gauge, river stage data were plotted for the most recent seven-day interval available at the time of download. If diurnal or semidiurnal fluctuations in river stage were apparent and

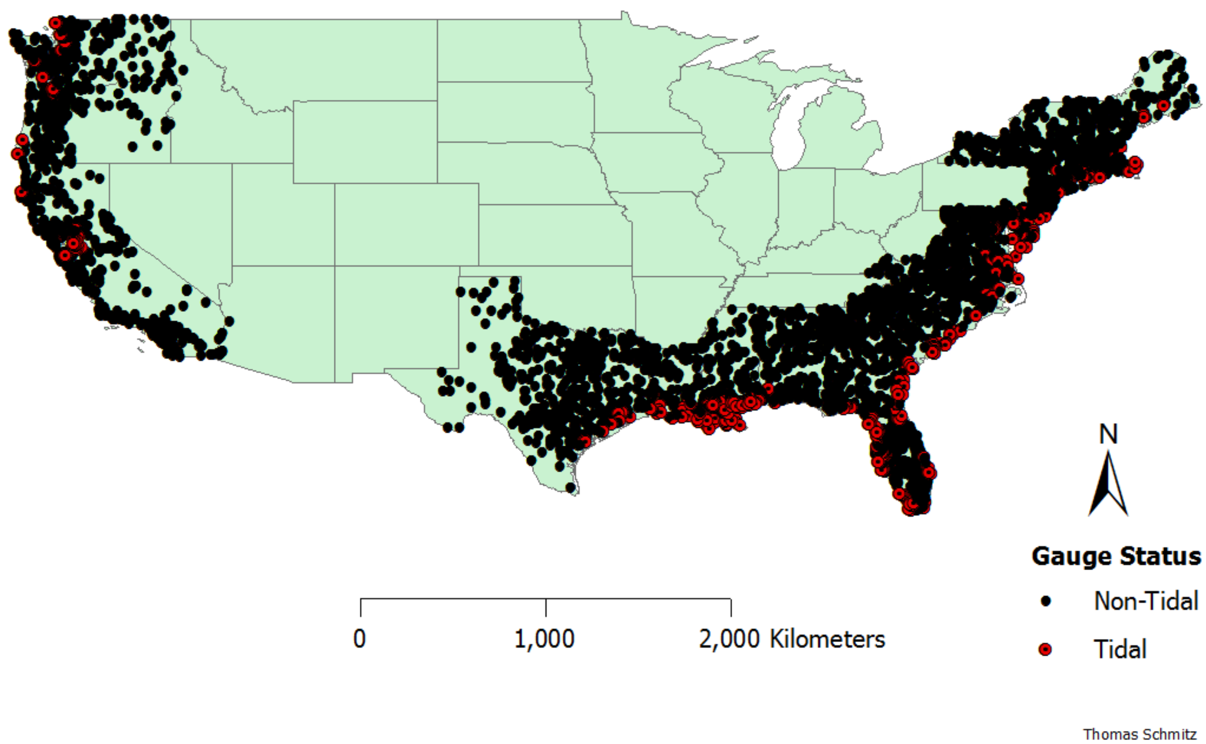

Figure 1. Dots represent USGS gauges analyzed for tidal influence. Tidally influenced locations are shown in red.

had a range of at least 3 inches, the gauging station was designated as tidally influenced (Figure 2). A database was created that includes USGS site identification number, latitude, longitude, elevation, site name, state, drainage area, contributing drainage area, and tidal or non-tidal designation.

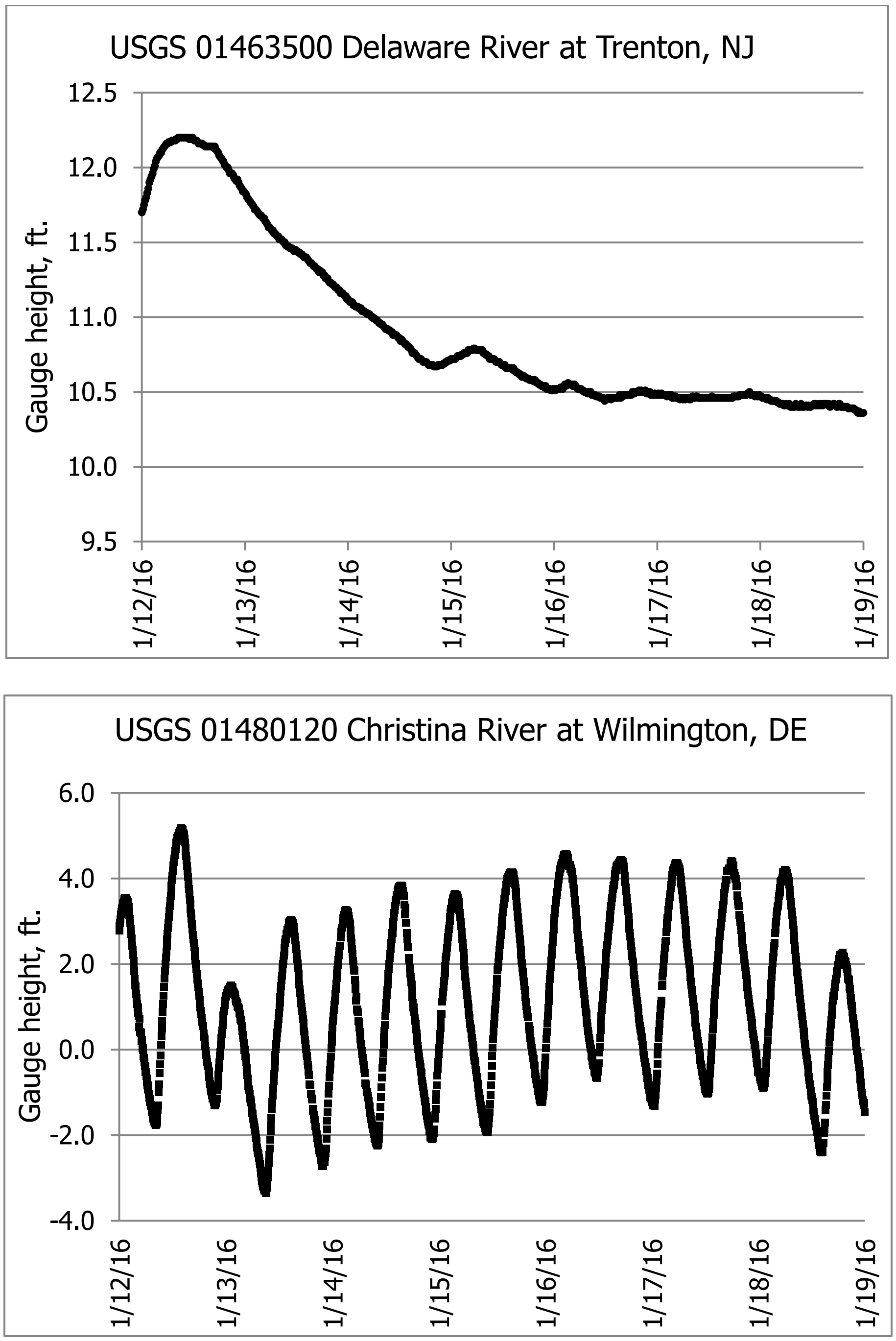

Figure 2. Example hydrographs of a non-tidal site (upper) and tidal site (lower).

The database was imported into ArcMap as a point feature class. River hydrography was also imported from the National Hydrography Dataset (NHD) database (U.S. Department of the Interior, NHD). In ArcMap, I analyzed several major parameters that I hypothesized might influence the distribution of tidal rivers, including distance from the coast, elevation, river size, and relationship to dams. I calculated the distance of each tidal gauge from the coast using the nearest linear distance function in ArcMap. I also assessed relationships between gauging station elevation (as reported by the USGS) and tidal influence. The USGS defines elevation for each station as the position of the land surface and/or gauging instruments relative to the North American Vertical Datum. To test the effect of river size on tidal influence, I extracted stream order at each gauging station from the NHD database. To test whether major structures such as dams impede tidal propagation, I imported locations of dams, weirs, lock chambers, and non-earthen shores from the NHD database (U.S. Department of the Interior). I visually examined positions of tidal gauges with respect to mapped dams and locks in the NHD database.

RESULTS

Eight percent of the 4,834 gauging stations are tidally influenced (383 stations). The USGS reports only 41 of these 383 stations as tidal. Tidally influenced gauges are located in close proximity to the coast (Figure 3), with 76% within 1km (linear), 85% within 5km, and 92% within 10km. At its farthest point, tidal influence extends 47km inland (station 01190070, Connecticut River, Conn.).

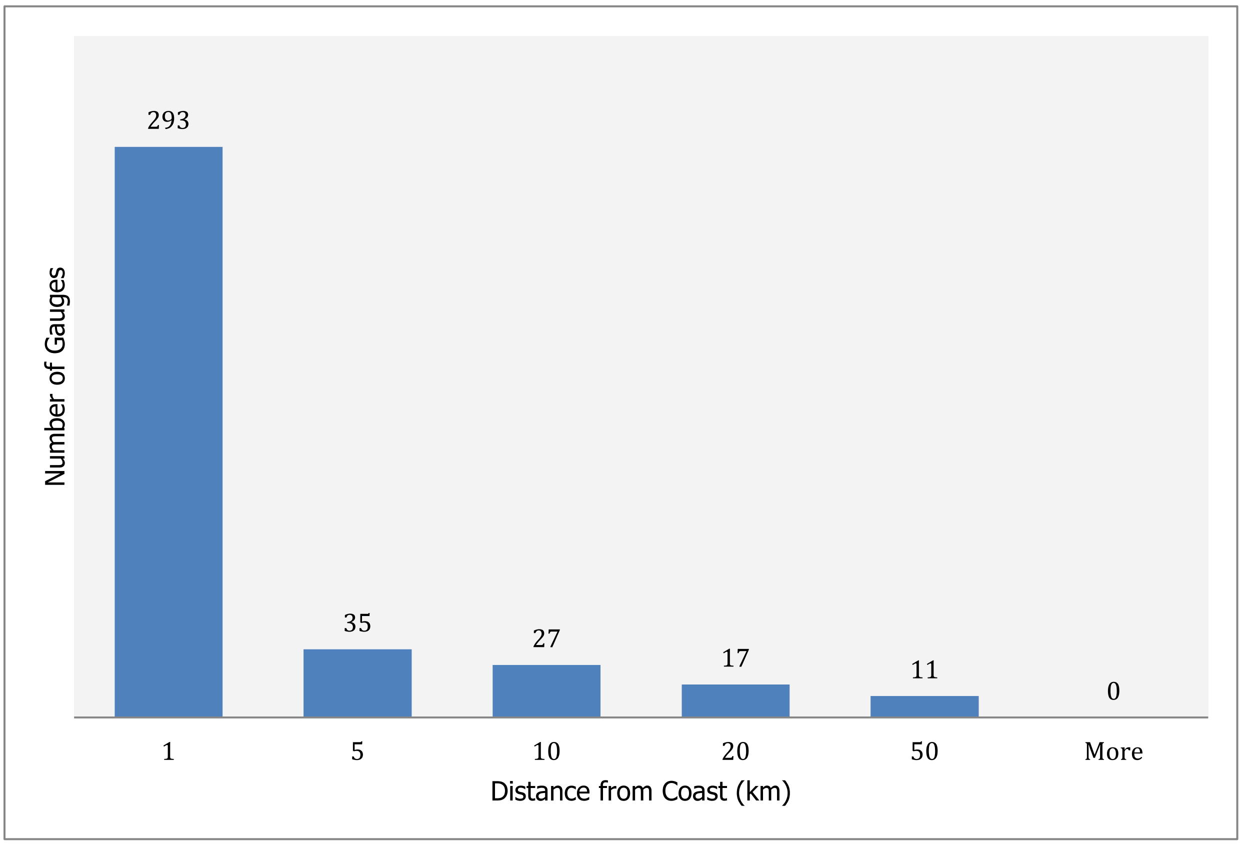

Figure 3. The number of tidally influenced gauges rapidly declines with distance from the coast. Distance is measured as a straight line from the gauge location to the coast.

The USGS reported elevation data for 248 of the tidal gauges and 3,877 of the non-tidal gauges analyzed (64% and 80%, respectively). Near the coast, the elevation of rivers varies widely and depends on topographic relief. For a given distance from the coast, tidal gauges tend to lie at lower elevations (Figure 4). The mean elevation for the tidal sites is -0.29 m (below North American Vertical Datum), with the highest gauge at 3.77 m.

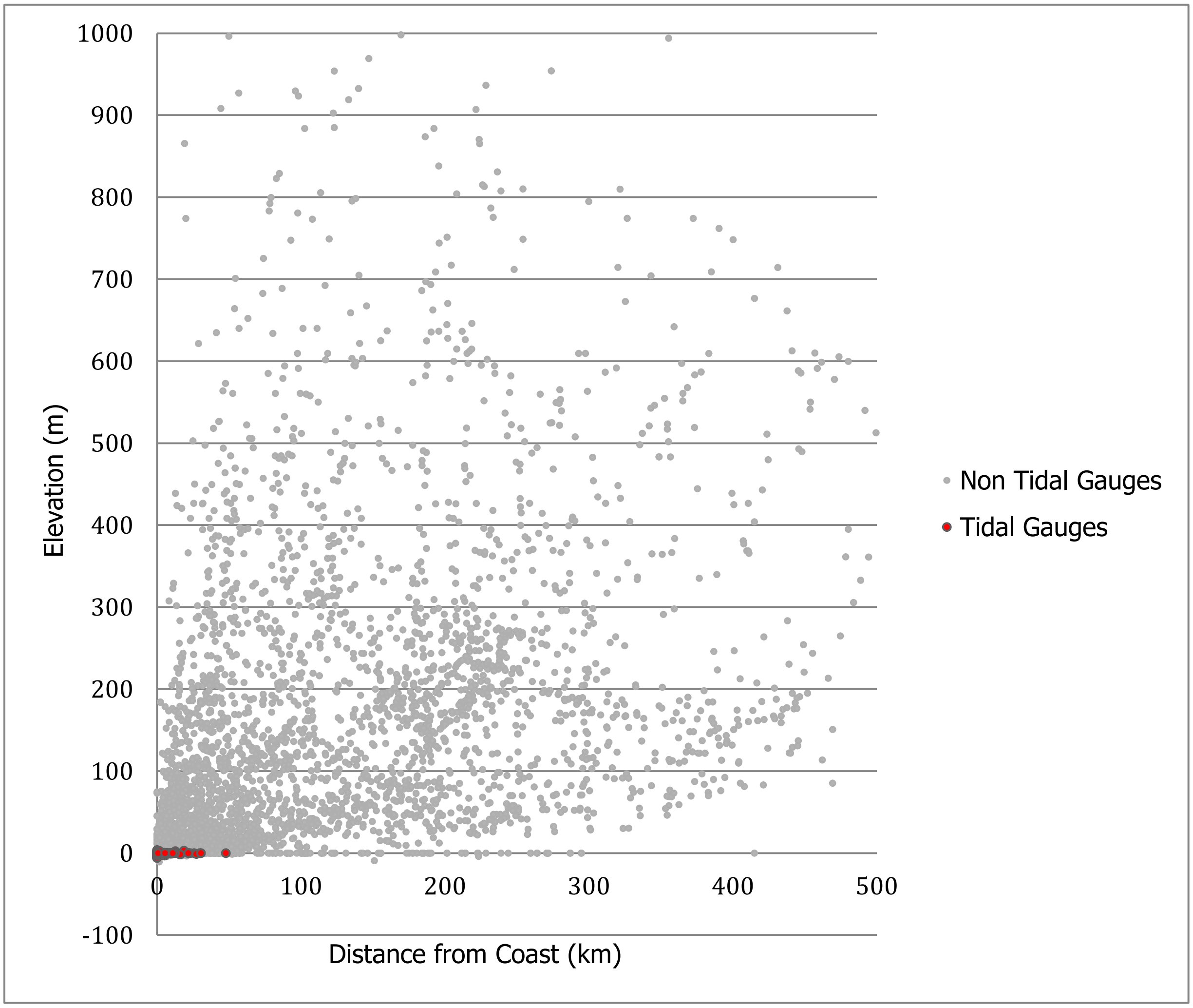

Figure 4. Tidal gauges are found at low elevations in close proximity to the coast.

The National Hydrography Dataset's (NHD) river network contains stream order values for each length of river. The majority of my analyzed gauges are on low to medium order streams, while less than 5% of all gauges are found on large rivers (with 8th order and higher) (Figure 5). Gauges with stream order of zero are mostly located on canals, ditches, bayous, and reservoirs. The representation of low order gauges is disproportionately greater in tidal than in non-tidal streams. This may suggest that tidal rivers are smaller or that biases in monitoring locations differ between tidal and non-tidal rivers.

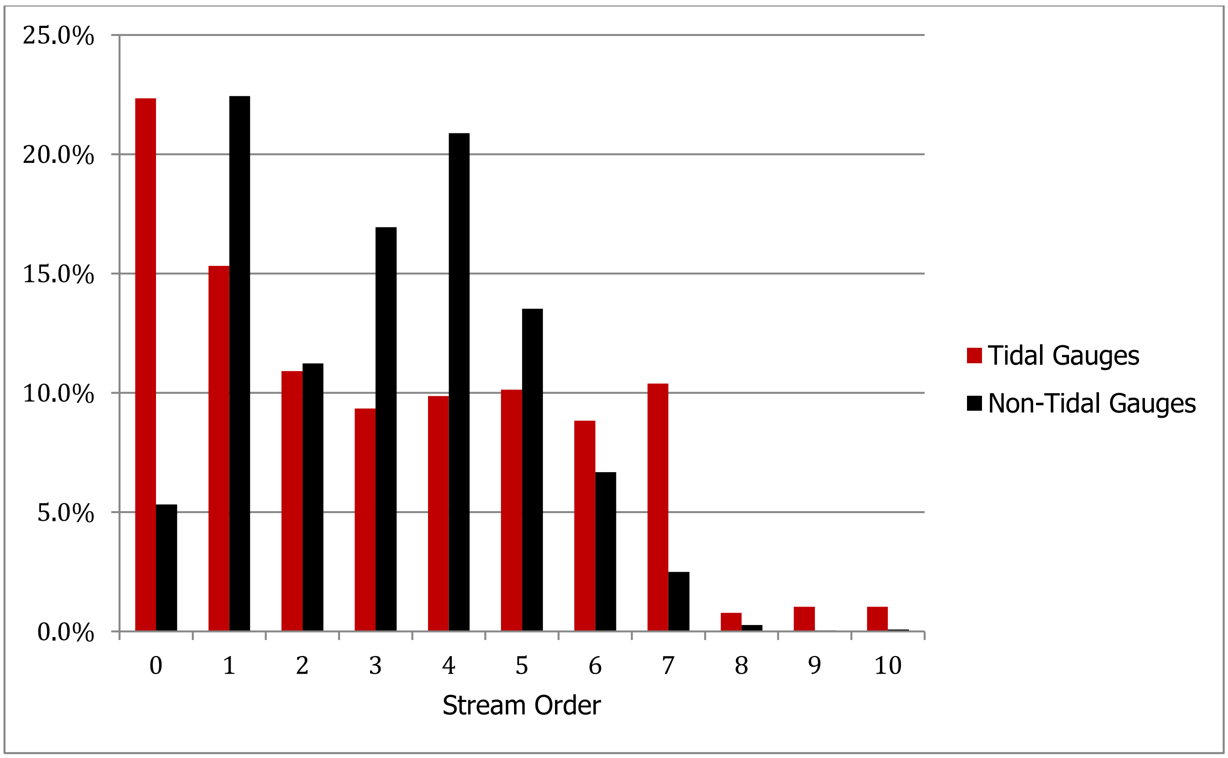

Figure 5. Frequency distribution of stream orders for tidal and non-tidal gauges.

In-stream structures can also affect tidal extent. Engineered features such dams and lock chambers or natural features such as waterfalls can block the movement of water, limiting the fluctuation in water height caused by the tides. One clear example where a dam forms the head of tides is the San Jacinto Dam near Houston, Texas

(Figure 6).

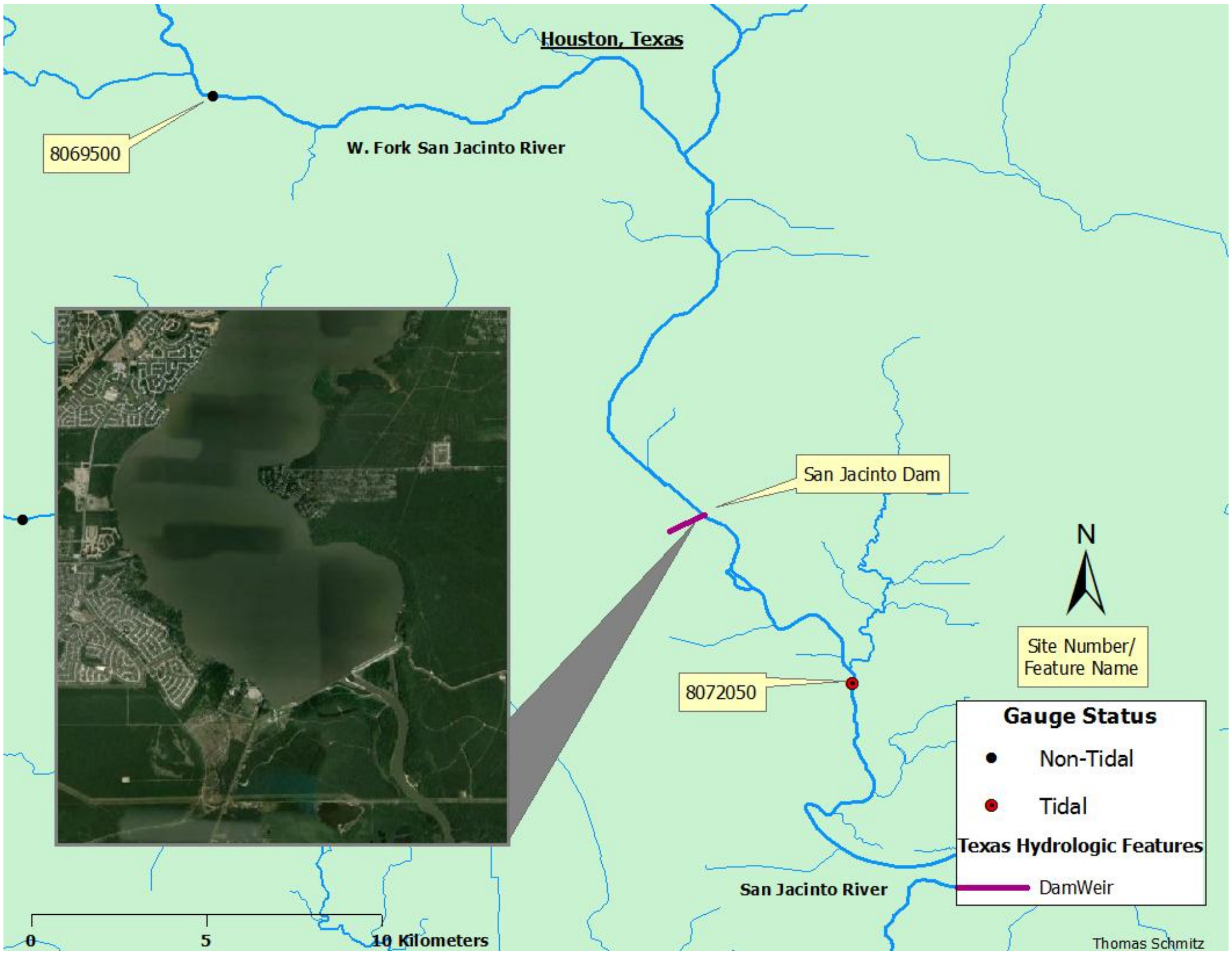

Figure 6. Upstream from tidal gauge station 8072050, The San Jacinto River is dammed to create Lake Houston. Above Lake Houston, station 8069500 is no longer tidal.

The NHD dam dataset does not include many low-head dams and other small features that may influence tides. In the Washington, D.C. area, a dam on the Potomac River appears to form the head of tides and is visible in Google Earth (Figure 7). Similarly, a set of engineered riffles in the nearby Anacostia River appears to form a tidal barrier. In both cases, there are non- tidal gauges (1646500, 1649500) immediately upstream of the features, and tidal gauges (1647600, 1651750) downstream, but the NHD database does not show any dams or other features (Figure 7). Thus, the NHD database has limited utility for resolving relationships between tidal extent and in-stream structures.

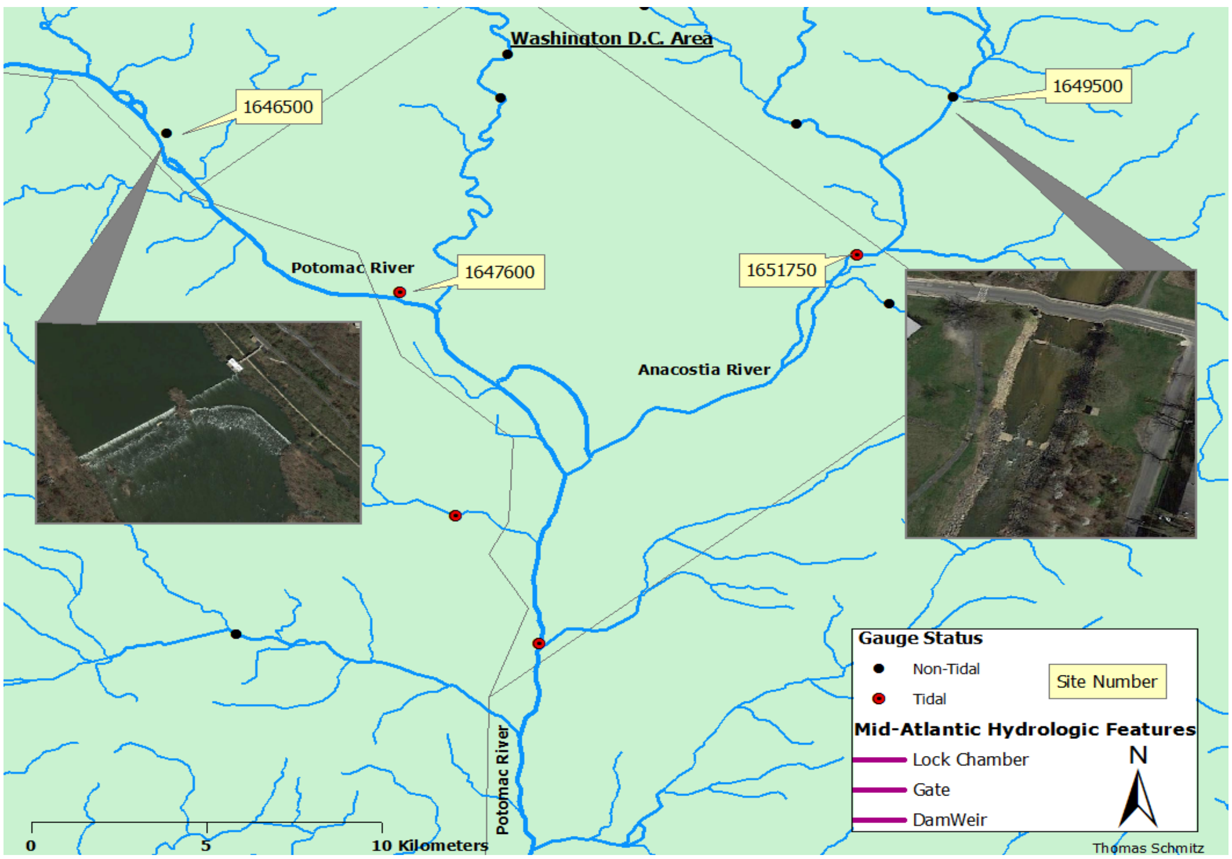

Figure 7. A dam on the Potomac River and engineered riffle on the Anacostia River are not included in NHD dataset. These features appear to form tidal barriers.

In some coastal regions, gauges were non-tidal due to other factors. One example is California's southern coast near Los Angeles (Figure 8). Atascadero Creek, Las Flores Creek, and The San Diego River appear to terminate in a beach or other land barrier before reaching the Pacific Ocean. The nearest upstream gauges exhibit no tidal influence, despite being in close proximity to the ocean. In general, tidal gauges are strikingly absent in Southern California (Figure 1). The sites closest to southern California with tidal influence are several hundred kilometers north around San Francisco, where a group of gauging stations monitor a large estuary (Figure 1).

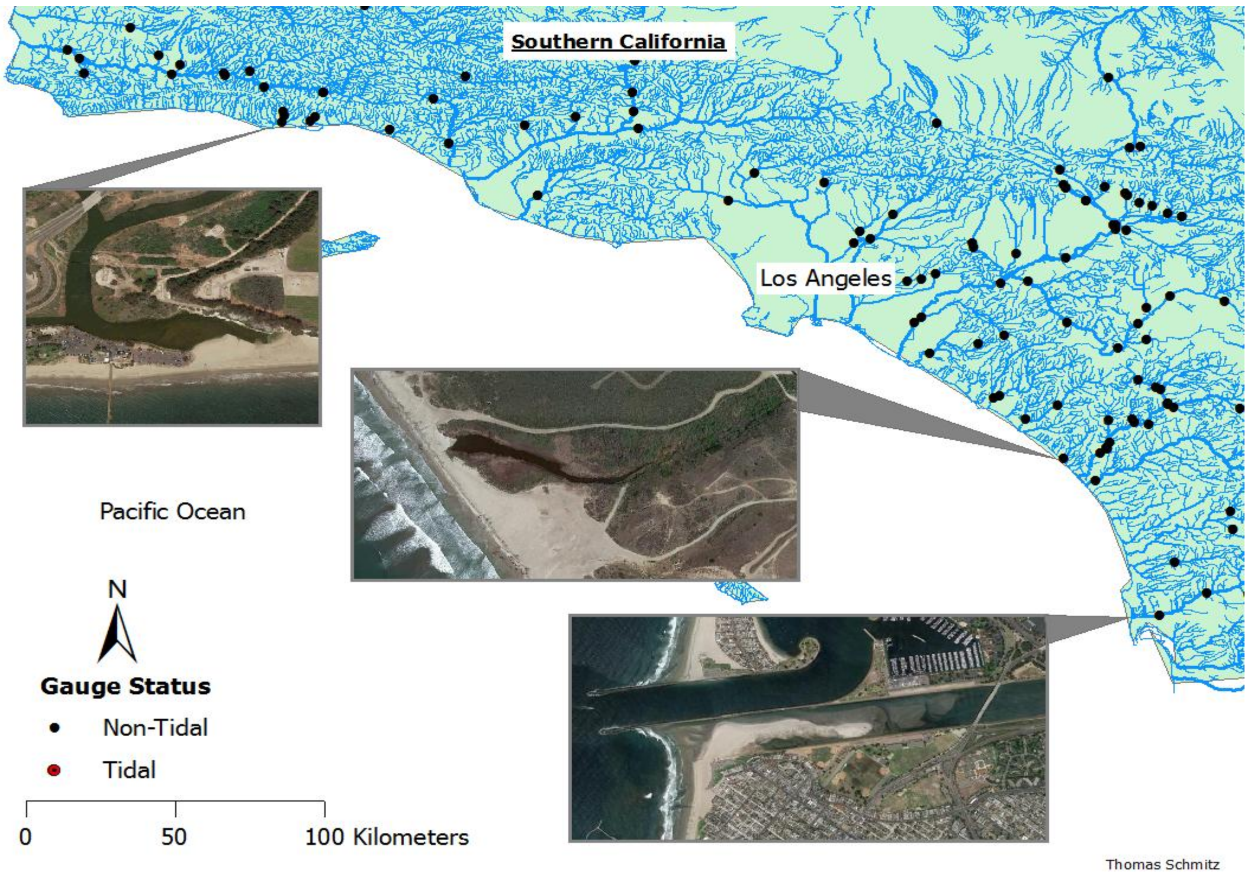

Figure 8. USGS gauging stations in Southern California are not tidally influenced. At a majority of the sites, the rivers are not connected to the ocean. Inset aerial photographs from left to right: Atascadero Creek, Las Flores Creek, and San Diego River.

DISCUSSION

River elevation and distance from the coast strongly influence the distribution of tidal rivers (Figure 4). Tidally influenced gauges typically have very low elevations: their mean elevation is -0.29 m . Additionally, 76% of the tidal gauges are within 1km of the coast (Figure 3). I hypothesized that stream size might also influence the distribution of tidal rivers. Specifically, tides should propagate farther inland in larger rivers because friction should dissipate the tidal pressure wave faster in small streams. However, tidal gauges were roughly evenly distributed across low and mid order streams (Figure 5). One possible explanation is that river size is not as important as elevation in controlling tidal propagation. However, another possible explanation is that the tidal zones of mid and high order streams are preferentially under-sampled near the coast. Alternatively, dams and other structures that impede tides may be more common on larger rivers and may limit tidal influence to small, free-flowing streams. It is clear that both engineered and natural barriers contribute to the low number of tidally influences gauges (Figures6-8). There are over 87,000 dams in the United States alone (U.S. Army Corps of Engineers) and only 21 rivers over 1000km long in the world that drain into the sea undammed (World Wildlife Fund, 2006). There exists a need to understand how humans have impacted the extent of tidal influence through dams and other structures.

Overall, only 8% (383) of the 4,834 gauges analyzed are tidally influenced, and the amount of data available for tidally influenced gauges is far more limited than for non-tidal gauges. USGS gauging stations vary by both the type of instantaneous data collected and the amount of data available. All sites contain identifying information (i.e. site name, site identification number, latitude and longitude) and continuous stage data, but only some gauges have other continuous information such as discharge or basic water quality parameters. For example, 80% of the total 4,834 gauges have discharge (m^3/s, ft^3/s) data available. In order to generate a continuous discharge record, USGS must create a site-specific rating curve, which is difficult in tidally influenced rivers. During rising tide, river flow stagnates or even reverses, leading to a hysteretic relationship between stage and discharge (Musial et al., 2015). The technology for making continuous velocity and discharge measurements is improving and should be implemented in tidal rivers, since accurate discharge measurements are essential for understanding nutrient loads to the coast.

Tidal gauges often lack basic site information. For example, drainage area has been analyzed for 89% of the 4,451 non-tidal gauges but only 32% of the 383 tidal gauges. Drainage area may be difficult to analyze in tidal settings where flow directions may reverse. However, even simple metrics like site elevation may be unavailable at tidal gauges. Site elevation is available for 87% of the 4,451 non-tidal gauges but only 64% of the tidal gauges.

Conclusions

Tidally influenced rivers are important components of the coastal hydrological system. I have explored a few factors that determine the extent of tidal influence. Tides generally influence USGS gauging stations that are in close proximity to the coast and at very low elevations. 76% of tidal gauges are within 1km of the coast, and the mean elevations of all tidal gauges is -0.29m. Manmade structures such as dams and natural river features such as riffles and waterfalls also act as tidal barriers to stop the inland flow of tides. Given the abundance of dams in densely populated coastal regions, it is imperative that we understand human disturbances to tidal rivers. A clear need exists to improve monitoring efforts in tidal rivers.

Suggestions for Future Research

Using freely available data from the USGS, this research can be expanded to the states of Alaska and Hawaii. Similar stage records may also be available in other countries that would allow global analysis. At the same time, a narrower field-based approach should also be taken by collecting stage and discharge data within a specific coastal river network or region, which would allow for a more in-depth look at the factors contributing to tidal propagation along coastal rivers.

Efforts should be made to monitor more tidal streams by installing a greater number of gauges in coastal areas and expand the NHD database by adding more dams and other hydrologic features. These efforts are the responsibility of the USGS and are dependent entirely upon increased funding.

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